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SELF-ORGANIZED CRITICALITY AND THE BARKHAUSEN EFFECT IN AMORPHOUS AND POLYCRYSTALLINE METALS

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13. ABSTRACT *(Maximum 200 words)*

An investigation of the possibility that the Barkhausen effect in amorphous and polycrystalline ferromagnets is an example of self-organized criticality is described. Since the theory of self-organized criticality was introduced by Bak, Tang, and Weisenfeld to explain the behavior of spatially extended, dissipative, dynamical systems, the Barkhausen effect is a natural candidate for such a description. The data are consistent with self-organized critical behavior: the power spectral densities depend on frequency f as $1/f^{a}$ and the distribution of pulse energies are well described by a power law analogous to the Gutenberg-Richter law for earthquakes. Alternative explanations for power-law dependences are also presented.

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INTRODUCTION

Bak, Tang, and Weisenfeld (ref 1) (BTW) introduced the concept of self-organized criticality (SOC) to explain power-law distributions and flicker noise in events associated with spatially extended, dissipative, dynamical systems such as earthquake faults. Jensen, Christensen, and Fogedby (ref 2) (JCF) clarified the analysis connecting power-law dependences and power spectral densities.

SOC has been explored through computer simulations of sandpile dynamics (ref 1), plastic flow in metals (ref 3), and earthquakes (ref 3). Experimental investigations include studies of actual sandpile dynamics (ref 4), sliding friction (ref 5), magnetic transitions in garnet films (ref 6), and the magnetic Barkhausen effect in an amorphous ferromagnetic alloy (ref 7).

Barkhausen phenomena appear to be ideal for description in terms of SOC and have many features in common with other SOC-related processes such as plastic deformation in metals and slip-stick at earthquake faults. In ferromagnets, (magnetic) hysteresis is produced by magnetic domains and their response to applied fields: for low applied fields, kinetic barriers permit only small reversible domain wall extensions and the system remains magnetically "elastic"; when the applied field is large enough to overcome these barriers (coercive force), the system enters a magnetically "plastic" regime characterized by large, random, irreversible domain wall jumps. These jumps generate Barkhausen noise, which may be detected by a coil placed near the sample. Magnetic hysteresis is analogous to mechanical hysteresis.

A brief summary of the results of a study of the Barkhausen effect as an example of SOC in three ferromagnetic materials: an iron base glassy metal, polycrystalline iron, and a nickel base polycrystalline alloy, alumel, is presented herein. A more extensive report has been published elsewhere (ref 8).

The data on the three materials are consistent with SOC. The distributions of pulse energy releases are well described by power laws with exponents similar to the Gutenberg-Richter law for earthquake distributions and the power spectral densities vary with frequency f as $1/f^{\alpha}$ (flicker noise). Furthermore, the distributions of pulse durations and areas also follow power laws, and the pulse distributions exhibit "size-effect" cutoffs at large amplitudes similar to those seen in sandpile simulations (ref 9).

EXPERIMENTAL

The amorphous alloy is a nominal 2-mil thick ribbon of Metglas 2605S ($Fe_{78}B_{13}Si_{19}$) from Allied-Signal cut into approximately 2-mm by 20-mm strips. The iron and alumel ($Ni_{95}Al_3Mn_2$) specimens were assorted lengths of 5 mil thermocouple wire obtained from Omega Engineering.

The samples were placed within a pickup coil located at the center of an air-core solenoid. A signal generator provided the sinusoidal current to the solenoid, which produces a field that continuously drives the sample through its B-H loop. The pickup coil registered trains of pulses that were amplified and recorded by a digital oscilloscope. The scan rate was selected to maintain suitable separation of individual pulses, while also providing an adequate number of pulses per train for analysis (typically 200).

THEORY

The central idea of SOC is that extended, dissipative, dynamical systems tend to evolve into critical states in which chain reactions of all sizes in time and space propagate through the system. Computer simulations indicate that the main features of SOC systems are power-law distributions of chain reaction sizes, $1/f^{\alpha}$ power spectral densities, and fractal structures.

JCF show that the power spectral density of a train of uncorrelated pulses (where each pulse represents a chain reaction) can be expressed as

$$S(f) = \frac{r}{(\pi f)^2} \int_0^{\infty} d\tau\, G(\tau) \sin^2(2\pi f \tau) \qquad (1)$$

where r is the pulse repetition rate and G(T) is a weighted distribution of lifetimes, defined as

$$G(T) = \int_0^{\infty} dA\ P(A,T)\ [A/T]^2 \qquad (2)$$

where P(A,T) is the joint probability for a pulse to have area A and length T. The equations hold for any distribution of uncorrelated pulses.

The present data are consistent with a simple power-law distribution of pulse lifetimes (as expected with SOC) modified by a sharp cutoff "size-effect." That is,

$$G(T) = T^{\alpha} H(T - T_c) \quad , \quad for\ t_0 < T < \infty \qquad (3)$$

where H(x) is the Heaviside function and the "size-effect" cutoff on pulse size is T_c. Such distributions of lifetimes yield (ref 10) power spectral density having the following form:

1. for

$$1/T_0 < f < 1/t_0 \quad , \quad S(f) \sim f^{-(3+\alpha)}\ when\ \alpha < -1 \qquad (4a)$$

$$\sim f^{-2} \qquad when\ \alpha > -1 \qquad (4b)$$

2. for

$$f < 1/T_0 \quad , \quad S(f) \approx constant. \qquad (4c)$$

JCF obtained similar results for an exponential cutoff "size-effect."

ANALYTIC PROCEDURE

The following steps were followed:

1. A systematic procedure for selecting a baseline and critical signal level was adopted to allow an unambiguous definition of individual pulses.

2. Pulse durations, areas, and energies were computed for each pulse.

3. Joint probability distributions P(A,T) and distributions of durations G(T) were computed from the area and duration data.

4. Power spectral densities were also determined directly via Fourier transform techniques (FFT algorithms, etc.).

RESULTS

A sampling of typical results is presented in this section. Figure 1 shows the distribution of Barkhausen pulse energies for the Metglas specimen: the power law with sharp cutoff at large pulse energies is illustrated. The power-law exponent is -1.60. Similar results are obtained for the iron and alumel samples with exponents -1.44 and -1.58, respectively. The distributions of pulse areas, durations, and weighted distributions of lifetimes (Eq. (2)) all follow similar power-law dependences.

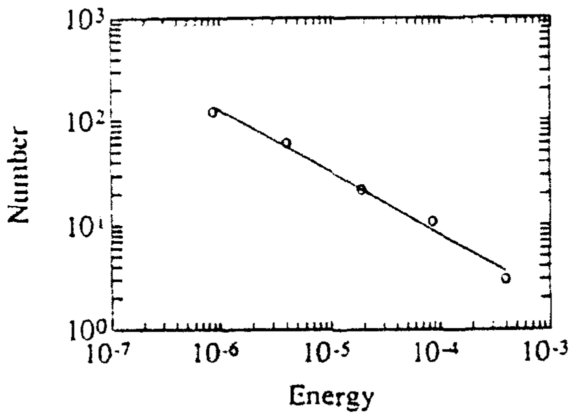

Figure 1. Distribution of pulse energies for the Metglas sample.

The results of Figure 2 illustrate the excellent agreement between power spectra for Metglas computed from pulse distributions via Eq. (1) and that obtained with FFT: the form of the power spectral density is consistent with Eq. (4).

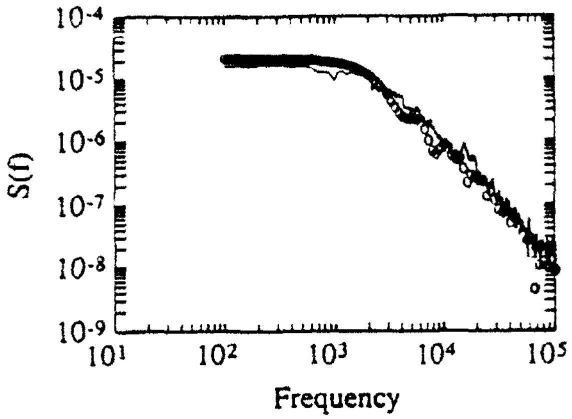

Figure 2. Power spectral density from Eq. (1) (circles) and from FFT (line) for Metglas.

DISCUSSION

Power-law distributions and $1/f^a$ dependences in the power spectra in these three very different ferromagnets suggest that the Barkhausen effect is an example of SOC phenomena. Furthermore, the resemblance of the Barkhausen distribution of energies and the distribution of earthquake energies (ref 3) suggests that they may belong to the same universality class.

However, another interpretation may be viable. As Mandelbrot (ref 11) has emphasized, fractal structure or fragmentation also gives rise to power-law distributions. Thus, complex pre-existing microstructure and the distribution of magnetic domains within the microstructure could follow a power law, which could then give rise to the observed power-law pulse distributions in the Barkhausen effect independent of SOC. (For example, Hornbogen (ref 12) has demonstrated the applicability of fractals to microstructures in metals.) Since Eqs. (1) through (4) would still apply, the power spectral density would also have the $1/f^a$ form characteristic of SOC under this interpretation. We will examine this possibility in future work.

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